

# **The Predictability of Extratropical Transition and of its Impact on the Downstream Flow**

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## **LONG-TERM GOALS**

To investigate the basic mechanisms that determine the predictability of tropical cyclones undergoing extratropical transition (ET) and of their subsequent impact on the downstream midlatitude flow.

## **OBJECTIVES**

To analyze the representation in the European Centre for Medium Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) of historical ET events in the western North Pacific using a combination of principal component and cluster analysis.

To investigate the sensitivity of the EPS forecasts to the initial ensemble perturbations associated with the typhoon undergoing ET and to stochastic physics.

To assess the variability in the structure of the low-level wind field during ET using results from idealized model calculations.

To investigate the mechanisms by which the tropical cyclone modifies the downstream flow using idealized modeling and potential vorticity (PV) inversion.

## **APPROACH**

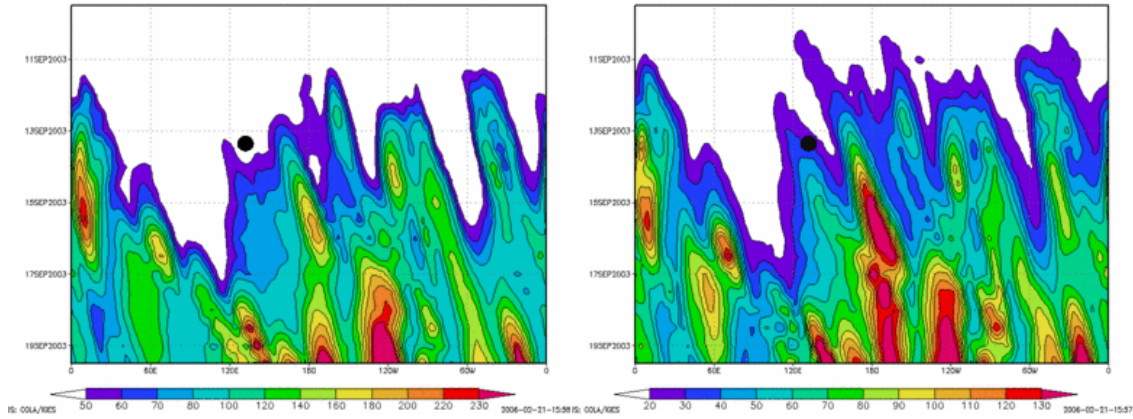
### **a. ECMWF Ensembles**

In order to investigate the variability of the ensemble members in association with extratropical transition we analyse cases of ET in the western North Pacific using principal component (PC) analysis and clustering techniques (Harr et al. 2006).

The leading empirical orthogonal functions (EOFs) are calculated for the region of interest. They identify the locations where the variability of the ensemble members is largest i.e. the centers of action. The leading EOF identifies the dominant synoptic pattern that contributes most to the forecast variability. Ensemble members with similar synoptic features are grouped by building clusters in which the members contribute in a similar way to the largest EOFs. For this purpose we apply a c-

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means fuzzy clustering algorithm to the first two principal components. The fuzzy clustering algorithm reassigns membership factors to each ensemble member indicating to which percentage that member belongs to every cluster. An ensemble member is only assigned to a cluster if the membership factor is larger than  $\sim 80\%$ . The number of clusters is determined by starting from 2 clusters, adding a further cluster iteratively and examining the resulting patterns.



**Figure 1: Hovmoeller plot for forecast from 9 September 2003, 12 UTC: root mean square difference (RMSD) of ensemble forecasts with perturbations averaged over  $40^{\circ} - 50^{\circ} \text{N}$  for 200 hPa (left) and 500 hPa (right). The high values of RMSD spread downstream from Typhoon Maemi (black dot) at both levels.**

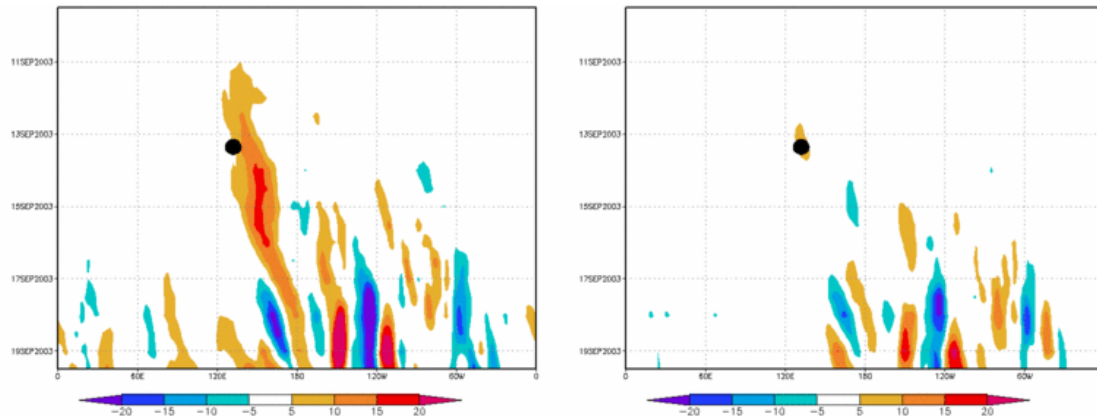
If the new cluster does not yield a distinctly new pattern the clustering is not continued. The cluster analysis adds significant value to the EOF analysis by enabling us to follow the synoptic evolution of the individual clusters.

In the ECMWF EPS initial perturbations for the ensemble members are obtained by calculating singular vectors with linearized diabatic physics for areas targeted around tropical cyclones. We rerun EPS forecasts both with and without perturbations targeted on a specific tropical cyclone. In order to identify the impact that is caused by the initial perturbations alone we switch off the stochastic physics for all experiments.

## b. Idealized Modeling

A full physics idealized modeling study is used to explore the variability in both the structure of the tropical cyclone undergoing ET and in the interaction of the tropical cyclone with the downstream flow. Special attention is paid to the role of the outflow in perturbing the midlatitude tropopause and exciting Rossby wave trains. The study uses the fifth generation NCAR / Penn State mesoscale model (MM5) in which we have implemented periodic boundary conditions. We use a channel configuration with the full latitudinal variability of the Coriolis parameter, as in Balasubramanian and Garner (1997). The channel is approximately 18 000 km in the east-west direction and 11 000 km in the north-south direction with 60 km horizontal resolution. A tropical cyclone is inserted in a variety of baroclinic wave cycles that are excited by variation of the initial perturbation. A nest with 20 km resolution covers the immediate vicinity of the transforming tropical cyclone. The sea surface temperature is a

time invariant function of latitude. By varying the initial structure, intensity, and position of the tropical cyclone along with the baroclinic lifecycles a variety of realistic ET events can be simulated.



**Figure 2:** *Forecast from 9 September 2003, 12 UTC: RMSD of ensemble forecast with perturbations minus RMSD of ensemble forecast without perturbations around Maemi at 200 hPa (left) and 500 hPa (right). The differences between the two ensemble forecasts are especially noticeable downstream of Maemi.*

## WORK COMPLETED

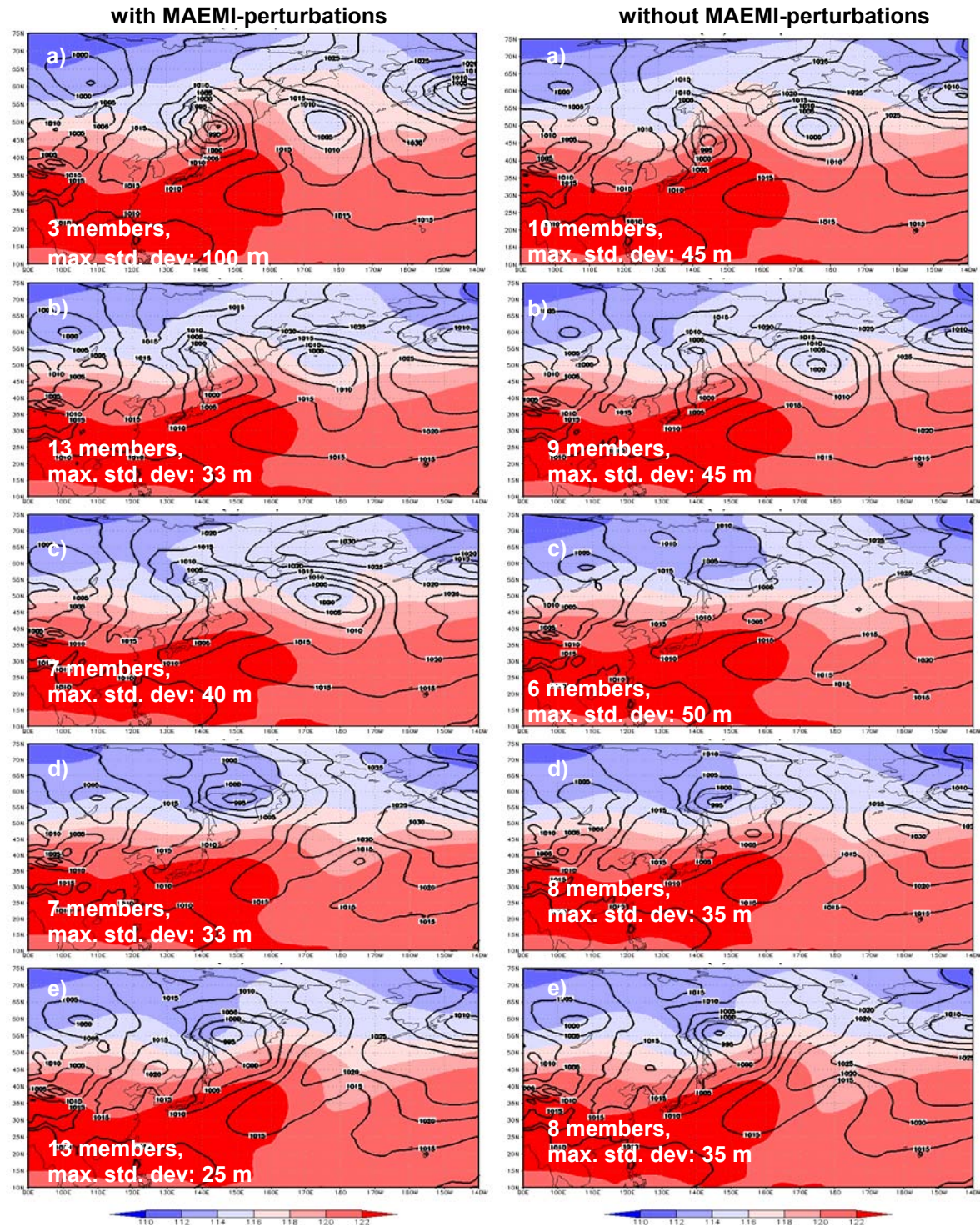
Case studies of Typhoons Maemi (2003), Tokage (2004), Nabi (2005), Saola (2005) and Hurricanes Fabian (2003), Philippe (2005) have been concluded. Sensitivity tests and diagnostics of the idealized experiment with a straight midlatitude jet have been completed. Both of these studies are being prepared for publication.

## RESULTS

### a. ECMWF Ensembles

Experiments have been carried out with and without singular vectors targeted on Typhoon Maemi (2003). The root mean square difference (RMSD) of the ensemble members (a measure of the ensemble spread) averaged over  $40^{\circ}$  -  $50^{\circ}$  N is presented in Hovmoeller plots of 200 hPa (left) and 500 hPa (right) heights in Fig. 1. Downstream of the ET of Maemi (black dot) a local maximum of the RMSD can be seen both in the 200 hPa and in the 500 hPa plot at about  $180^{\circ}$  E at 15 and 16 September. At 200 hPa it becomes smaller again at 17 September which indicates that the 5- and 6-day forecasts for this region are worse than the 7-day forecast. In spaghetti plots of the ensemble members (not shown) it becomes clear that this uncertainty is associated with different representations of a trough downstream of Maemi. After 7 days the flow becomes more zonal again in all the ensemble members.





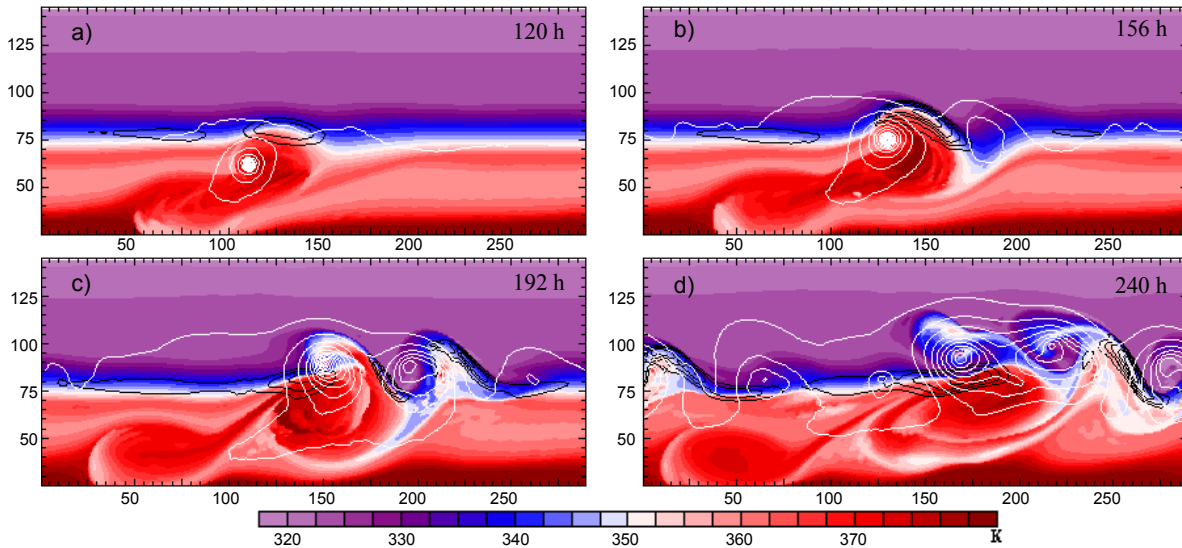
**Figure 3:** (on following page) Potential temperature on the dynamic tropopause ( $PV=2 \times 10^{-6} \text{ kg}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ K}$ ) of the 5 clusters in the ensemble calculated with (left) perturbations and without (right) perturbations around Maemi. Number of members and standard deviation of the members in each cluster is marked in white at the bottom of the figures. Clusters differ through the “waviness” of the tropopause and the strength and location of the ET system.

To identify the influence of the initial perturbations targeted on Maemi the difference between the RMSD relative to the control forecast with and without perturbations has been calculated for forecasts from 9, 10 and 11 September 2003 12 UTC. The results for 9 September are shown in Hovmoeller plots in Fig. 2. A signal which originates at the ET time and position of Maemi propagates downstream and broadens with increasing forecast time (Fig. 2). At 200 hPa (left) quite high values can be seen in an area including the typhoon itself (black dot) and an existing downstream ridge. The values of these differences are almost entirely positive until 17 September, indicating an increase of the ensemble spread in the run with perturbations. From 17 September on they show an alternate pattern of positive and negative values. This indicates a displacement of waves between the runs with and without perturbations. The maximum of the differences at 200 hPa on 15 September makes up 25 % of the RMSD of the forecast with perturbations (Fig. 2 left). The absolute values of the signal at 500 hPa (Fig. 2 right) are smaller than at 200 hPa though if compared to the runs with perturbations on this level (Fig. 1 right) it can be seen that the signal in the region of Maemi represents 20 % of the values on the same position in Fig. 1 (right). In the same plot of differences at 500 hPa (Fig. 2 right) with smaller scales it can be seen that the values of the signal are mostly positive until 15 September 12 UTC. After that time the same alternating pattern of positive and negative values

In this example the 200 hPa height is used for the PC and cluster analysis. Five clusters are found for the 5-day forecast from 9 September 2003 12 UTC (verification time is 14 September 2003 12 UTC) of both runs with and without perturbations. Clusters of the runs with perturbations are shown on the left and those without perturbations on the right of Fig. 3. The number of ensemble members and the standard deviation between the ensemble members in each cluster is marked in white on the bottom of each panel. In the interest of clarity the runs with perturbations are referred to as “PERT” and the runs without perturbations as “NOPERT” in the following.

In a brief comparison it can be seen that the 200 hPa flow can be split up in two different patterns. One is quite “wavy” and has a clear trough-ridge-trough pattern between 130° E and 170° W at about 35° - 60° N. It is referred to as “meridional” in the following. The other one is rather zonal west of 160° E and has a sharp trough at about 180°. It is referred to as “zonal” in the following. In PERT three meridional and two zonal flow patterns can be found, in contrast to two meridional and three zonal patterns in NOPERT. It is characteristic for the zonal flow patterns that they do not show the downstream deep pressure system that can be found in all the meridional flow patterns. The location of the ET-system is represented quite differently in the clusters. However, all the meridional flow patterns show the ET location further to the west than the zonal patterns. The minimum pressure of the ET system in the clusters ranges from 1005 hPa to 985 hPa for PERT (Fig. 3 b, left) and from 1005 hPa to 990 hPa for NOPERT (Fig. 6 b, right). The cluster that shows the strongest ET (Fig. 3 a) cannot be found in NOPERT. This is a small cluster with only three members. Fig. 3 e) shows a weak deep pressure system in the location where the ET system should be. In further time steps (not shown) it can be seen that this system is in the process of decaying. This is the only cluster that shows decay after recurvature. A cluster like this cannot be found in NOPERT. Even the cluster in Fig. 3 f) reintensifies in a later time step (not shown).

The standard deviation within each cluster gives an indication of how well defined the clusters are. We found that in the region of the ET system and the downstream ridge the standard deviations were highest. The values are on average approximately 30%, higher in the clusters of the runs without perturbations. The small cluster in PERT that shows the strongest ET is the only exception.



**Figure 4: Potential temperature on the dynamic tropopause ( $PV=2 \times 10^{-6} \text{ kg}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ K}$ , colour), surface pressure (white contours, every 5 hPa) and wind speed on 200 hPa exceeding  $40 \text{ m s}^{-1}$  (black contours, every  $5 \text{ m s}^{-1}$ ) for times 120 h (a), 156 h (b), 192 h (c), and 240 h (d) into the integration of the straight jet experiment. The scale of the axes is in grid points.**  
**[Figure describes the temporal evolution of the reference numerical experiment of the interaction of the tropical cyclone with an initially straight jet stream. Formation and amplification of a ridge-trough couplet and a jet streak is shown.]**

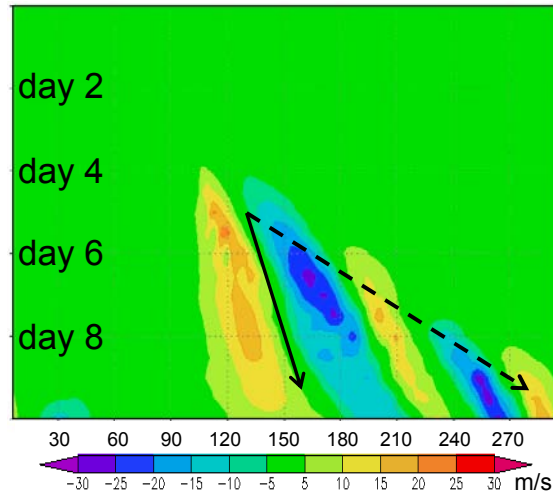
We can conclude that the range of possible developments in PERT is larger than in NOPERT so that the probability that the analysis lies outside the ensemble is reduced. In addition, the clusters are more clearly defined in the runs with perturbations than in the runs without perturbations and therefore a higher probability can be assigned to the individual clusters.

## b. Idealized Modeling

In our basic experiment a tropical cyclone interacts with the most simplified representation of the midlatitude flow regime: a straight jet. The prominent features of the interaction are a jet streak that forms in the region where the outflow of the tropical cyclone impinges on the jet and a ridge-trough couplet on the tropopause. Both features amplify during the interaction. Beneath the left exit region of the jet streak rapid surface cyclogenesis takes place. At upper levels the ridge-trough pattern extends downstream as a wave pattern and initiates a family of cyclones (Fig. 4). The temporal evolution of the upper-level wave pattern can be interpreted as the excitation of a Rossby wave train by the ET event and its subsequent propagation downstream (Fig. 5). Seclusion of moist tropical air is found around the centre of the mature ET system in lower to middle levels and transport of moist, warm air into the midlatitudes might be enhanced along the cold front of the ET system.

Sensitivity experiments highlight the importance of the atmospheric state in the midlatitudes for the propagation of the Rossby wave train. Consistent with the theory of Rossby wave propagation on a localised barotropic jet (Swanson et al. 1996) we find a higher group velocity for stronger jet streams.





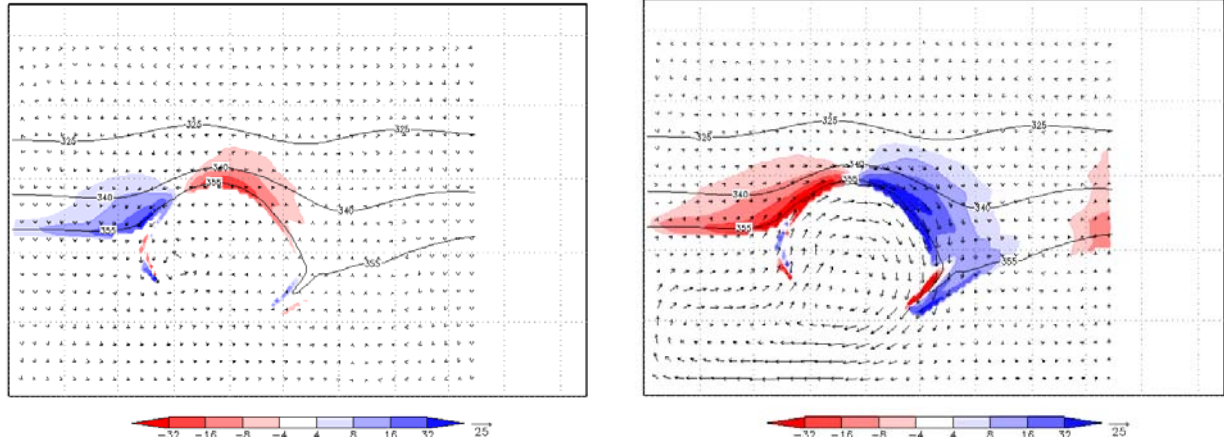
**Figure 5: Hovmoeller plot of the 200 hPa meridional wind speed of the experiment depicted in Figure 4 (meridionally average from grid point 60 to 120). Excitation of a Rossby wave train can be seen around day 4, the subsequent propagation can be identified in the alternating occurrence of northerly and southerly winds spreading eastward with time. The solid arrow denotes the movement of the ET system, the stippled arrow the eastward propagation of the Rossby wave train. The scale of the x-axis is in grid points.**

For a stronger jet we also find a greater wave length. For a weaker jet it is found that the primary downstream system develops in a more meridional orientation of the upper-level flow and exhibits a greater tendency to the anticyclonic paradigm of life-cycle behaviour (Davies et al. 1991, Thorncroft et al. 1993). Baroclinic feedback by deeper surface systems and midlatitude diabatic processes are found to be important for the amplitude of the Rossby wave train. However, the wave length and group velocity of the Rossby wave train do not seem to be influenced by moist processes.

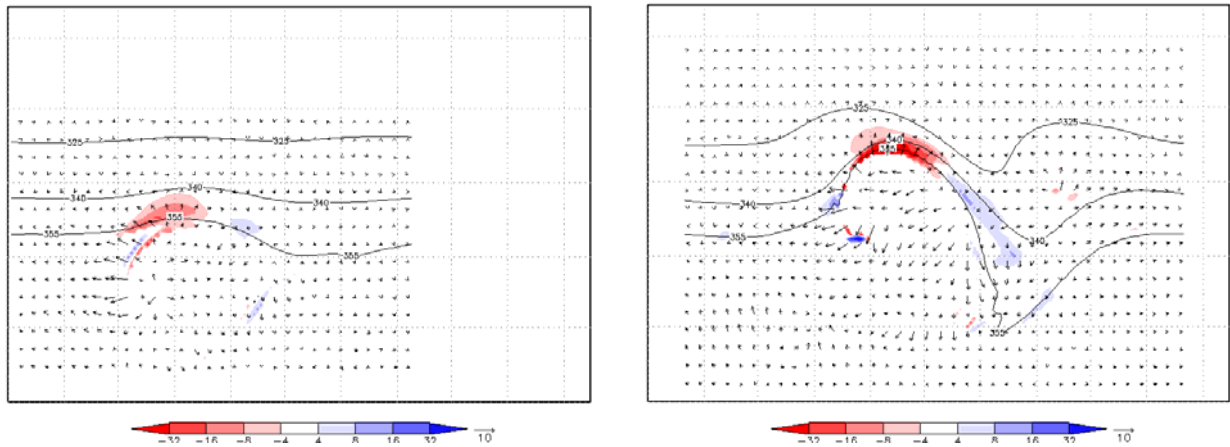
Piecewise PV inversion shows that the cyclonic circulation of the decaying positive PV tower of the ET system is an important contributor to ridge building (Fig. 6). The divergent component of the flow is equally important, in particular later in the interaction. In our analysis the divergent flow cannot be attributed to distinct flow features. In the early stage of the interaction it is indicative that divergence associated with the outflow layer contributes to the ridge building. Later in the interaction the divergent flow seems to be related to the secondary circulation associated with the jet streak (Fig. 7). The impact of low-level temperature and PV anomalies on the building of the ridge is negligible. It is shown that adiabatic advection of potential temperature ( $\theta$ ) along the dynamic tropopause alone can be accounted for the formation of the ridge.

The balanced effect of the outflow layer is mainly to intensify the downstream trough (Fig. 6) and to form a streamer of low  $\theta$ -air extending far into the south of the model domain. The effect of the outflow layer on trough formation is also apparent in sensitivity experiments using different cyclone structures. In an experiment with a tropical cyclone with a less pronounced outflow layer there is less meridional orientation of the downstream flow and the primary downstream system tends to exhibit a more cyclonic life-cycle. In our experiments a decaying ET system excites a less intense wave train and initiates a weaker primary downstream system in the moist midlatitude environment. The impact of the structure of the ET system is greatest one wave length downstream of ET.





**Figure 6:** Potential temperature ( $\theta$ , contour lines, labeled), balanced wind (arrows) and meridional advection of  $\theta$  (shaded) on the dynamic tropopause ( $PV=2 \times 10^{-6} \text{ kg}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ K}$ ) for PV anomalies associated with the positive PV tower of the tropical cyclone (left) and with the negative anomaly associated with the outflow layer (right) at 132h of the numerical experiment depicted in Fig. 1. Color shades denote values of 4, 8 and  $16 \times 10^{-5} \text{ K s}^{-1}$  for  $\theta < 360 \text{ K}$ . Northward advection of high  $\theta$ -values is shown in red colors, southward advection of low  $\theta$ -values in blue. Note the different scaling of the wind arrows. The advection pattern close to the boundary of the inversion domain is affected by the boundary conditions and might not be physically meaningful. Advection of high  $\theta$ -air in the crest of the ridge and advection of low  $\theta$ -air in the base of the trough amplifies the ridge-trough pattern.



**Figure 7:** same as Fig. 6, but for the divergent flow at 108h (left) and 156h (right). Divergent flow contributes to ridge building, as can be seen in the advection of high  $\theta$ -air in the crest of the ridge.

Adiabatic advection of  $\theta$  on the dynamic tropopause by the balanced flow is the dominant mechanism for the formation of the ridge-trough couplet. However, the formation and maintenance of the PV anomalies inducing the advecting flow field (namely the positive PV tower and the outflow anomaly) crucially depend on moist processes. The structural evolution of a tropical cyclone during ET should therefore impact the timing, structure and intensity of a developing extratropical cyclone in the adjacent downstream region.

## **IMPACT/APPLICATIONS**

The analysis of the EPS forecasts can contribute to the development of diagnostic tools for forecasters. The idealized modeling study helps us identify the processes that are most important during ET and thus can contribute to future model developments.

## **RELATED PROJECTS**

This work is carried out in collaboration with Prof. Patrick Harr (Tropical Cyclone Formation/Structure/Motion Studies, award number N0001406WR20257). Access to the ECMWF ensembles is possible through a special project entitled “The impact of tropical cyclones on extratropical predictability” and in collaboration with Dr. Martin Leutbecher of ECMWF.

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## **PUBLICATIONS**

Jones, S. C., Anwender, D., and Riemer, M., 2006: Die Umwandlung tropischer Wirbelstürme in außertropische Tiefdruckgebiete und ihr Einfluss auf das Wetter der mittleren Breiten, *promet* 32, Heft 3-4, 130-134. <http://www.dmg-ev.de/gesellschaft/publikationen/promet.htm> [published, refereed]

### **Conference papers:**

3 Papers were presented at the WMO/TMRP International Workshop on Tropical-Extratropical Interactions, incorporating the Third Meeting of the International Workshop on Extratropical Transition, Perth, Australia, in December 2005:

Anwender, D., P. A. Harr, S. C. Jones: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: ensemble cases from 2005

Jones, S. C., D. Anwender, M. Leutbecher, P. A. Harr: Predictability Associated with the Downstream Impacts of the Extratropical Transition of Tropical Cyclones: Ensemble sensitivity to initial perturbations.

Riemer, M.: The impact of extratropical transition on the downstream flow: an idealized modelling study, presented at

4 papers were presented at the AMS 27th Conference of Hurricanes and Tropical Meteorology held in Monterey, California in April 2006:

Anwender, D., M. Leutbecher, S. C. Jones, P. A. Harr: Sensitivity of ensemble forecasts of extratropical transition to initial perturbations targeted on the tropical cyclone.

Harr, P. A., D. Anwender and S. C. Jones, 2006: Predictability associated with the downstream impacts of the extratropical transition (ET) of tropical cyclones.

Riemer, M.: The impact of extratropical transition on the downstream flow: idealized modeling study

Riemer, M., P. Hofheinz, S. C. Jones: Structural changes of low level wind field of tropical cyclones in idealized extratropical transition scenarios

## **HONORS/AWARDS/PRIZES**

Michael Riemer, IMK, awarded ‘The Max A. Eaton Prize‘ at the AMS 27<sup>th</sup> Conference of Hurricanes and Tropical Meteorology, 24-28 April 2006, Monterey, California sponsored by the AMS